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A Simplified Damage-following Model for Reinforced Concrete Columns

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SUMMARY

Nonlinear models are becoming a widely solution for seismic evaluation and design of new structures. The implementation of those models in engineering practice requires robust methodologies and guidelines about the consistent use of nonlinear analysis. Objective numerical models must be developed or, at least, the extent of the accuracy of each possible solution must be accounted for and its impact included within the safety verification framework. One particular issue that affects distributed inelasticity models is the consistency of the numerical model adopted. Not only is an analyst interested in global performance engineering demand parameters but also code-based procedures require that local response should be used in the assessment stage. Hence, it is important to reconcile local (Moment-curvature) and global (Force-drift) responses. The simplified damage-following models presented herein try to circumvent some issues associated with objectivity and user-dependent model selection. The considered models ensure correct capture of hardening behavior ranges and an objective response during softening. This is done by updating at each analysis step the inelastic zone length. A simple application is considered comparing experimental results from 1 RC column and regularized beam models available in OpenSees.

Key Words: *Damage, Regularization, Force-based, Reinforced Concrete, Model updating*

1 INTRODUCTION

The nonlinear cyclic analysis of RC members can be performed using different types of models which have been developed over the years and that require different levels of complexity in terms of modelling, analysis and interpretation of the results. From a practical point of view, frame models constitute an interesting option since, in Earthquake Engineering, the number of analyses that are required to assess the behaviour of a structure usually demands for a simple approach.

Nevertheless, the level of accuracy needs to be considered, since the simplicity of the model may involve inherent simplifications and omissions that can have a strong impact in the seismic demand results. The present study presents a simplified alternative method that can be used in OpenSees to evaluate the reliability of some of the current consistent methods involving static formulations (without adaptive properties) towards the implementation of modelling uncertainties in current performance-based methods.

2 SIMPLIFIED ADAPTIVE FORCE-BASED ELEMENT

Using a *low order* integration scheme available in OpenSees (Scott, 2011), an adaptive force-based beam column element based on Gauss-Lobatto integration was constituted, relying on the classical configuration of the method while hardening sectional response is observed and shifting towards a regularized approach when softening effects arise. This numerical method allows for the explicit specification of the position of all integration points (IPs) along with the correspondent integration weights.

In the proposed method, the extreme IPs (*i* and *j*) assume, when softening is verified, an integration weight which is equivalent to the characteristic length (L_p) of the beam column element. Several mathematical models can be assumed to compute the characteristic length, with higher or lower levels of complexity, including static data (i.e. constant modelling parameters) or response-based data (i.e. from the output of the analysis) to compute their values. Almeida *et al*. (2012a) defined that once softening is observed in a structural element, the IP weights must be recomputed under the assumption that the extreme integration weights are equal to λ_p. The value of λ_p can be calculated according to a given integration interval [a; b] using Eq.1.

$$\lambda_p = (b-a)\cdot\frac{L_p}{L} \tag{1}$$

When softening is identified in an integration point at the extreme position *i*, the correspondent integration point must reflect the expected characteristic length of the section. Hence, in this case the IP1 weight must be set in order to match the normalized characteristic length $w_1^* = \lambda_{pi} = 2\cdot L_{pi}/L$, since it is assumed that the domain [1; 1] corresponds to yielding (b-a)=2. Using interpolatory quadrature and taking the Vandermonde matrix, the additional integration weights can be computed according to Eq. (2). A similar strategy can be defined for the analysis of the additional cases, comprising the case when the IP at location *j* presents softening behaviour or representing the situation in which both extreme IPs enter in a softening range

$$\begin{bmatrix} w_2^* \\ w_3^* \\ w_4^* \\ w_5^* \\ w_6^* \\ w_7^* \end{bmatrix} = \begin{bmatrix} 0.391640 - 2.411088\cdot\lambda_{pi} \\ 3.011088\cdot\lambda_{pi} + 0.2883602 \\ 0.640000 - 3.200000\cdot\lambda_{pi} \\ 3.011088\cdot\lambda_{pi} + 0.2883602 \\ 0.3916398 - 2.411088\cdot\lambda_{pi} \\ \lambda_{pi} \end{bmatrix} \tag{2}$$

Using the routine *updateparameter* available in OpenSees, the initially defined integration weights (Gauss-Lobatto with 7 IPs) are updated to the new values and these new values are used in the next analysis step. The curvatures and bending moments recorded in the updating stage are taken also as the reference values to assess the softening condition in the next step.

An alternative method can also be considered using inelastic zone force-based elements has the one proposed by Scott and Fenves (2006). In this context, the regularized strategy formulated can be used to update the parameter Lp_1 and Lp_2 and the integration weights can be consistently obtained directly using the beam formulation available.

3 DAMAGE FOLLOWING CRITERIA FOR ADAPTIVE-MODEL

The adaptive formulation defined in the previous section requires that a criterion must be selected to update the characteristic length. Three alternatives can be considered in order to consistently represent the spread of the inelastic zone length in the beam columns.

a) A first method can be seen has an extension of classical models, and involves a single updating transformation of the initial hardening scheme suitable model to an inelastic zone model when a trigger condition (curvature or moment softening condition as proposed by Almeida *et al*. (2012a).
b) A second approach involves the use of an adaptive characteristic length at both sides of the structural element considering a linear development of the moment distribution along the height of the column. Using a reference moment (for instance the yielding moment or the concrete cover spalling moment) to compute the characteristic length, it is possible to identify the extent of the damaged zone and recalculate the integration weights in order to account for actual size of the inelastic zone. This can be done either using the full computation defined before or the simple strategy updating the hinge length in the Scott and Fenves (2006) model available at OpenSees.
c) A last approach can be seen as a fully automatic version of the adaptive model and involves the longitudinal steel strain profile in compression along the length of the member and using piecewise cubic interpolation functions. This approach has been proposed by Almeida *et al*. (2012b) and uses the constructed profile, which can benefit from the fact that 7IPs can be used to ensure hardening consistent responses, to compute the characteristic length corresponding to the extent of the reinforcing bar length that exceeds the yielding strain. In the present study, due to the update strategy assumed (i.e. updating at the end of each analysis step), an initial trigger condition was established which corresponds to the yielding curvature at the extreme section being achieved and the updating strategy was induced at every step at which an higher value than the previously recorded curvature is verified. An application of this strategy was studied in the present article. The main objective was to observe if a strategy involving instantaneous recorders for the response (available at OpenSees) in combination with the *parameter/updateparameter* commands would allow for the use of a simplified version of a damage-following beam-column element.

4 APPLICATION

The experimental results of the specimen S24-5T tested by Bae (2005) is presented herein for the evaluation of the proposed adaptive strategy. The column is 3.048 m high and has a sectional configuration according to figure 4, with 0.609 x 0.609 m^2. Details of the column and materials can be found in Bae (2005). The analysis of the results obtained for the strain based adaptive scheme composed by 7 IPs showed that a considerable level of accuracy was obtained with the current model. An approximate value of the experimental damage (0.28m) length was obtained

(Figure 1b). Figure 2 shows the consistent results also obtained for the global and the local response at the base section of the column even at large softening stages.

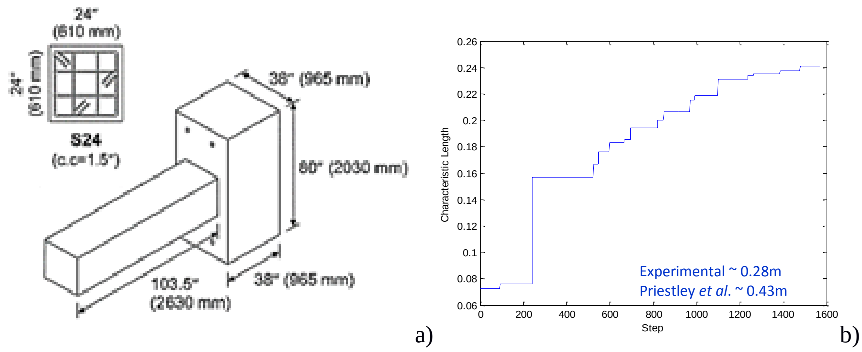

Figure 1. Case study: column S24-5 from Bae (2005).

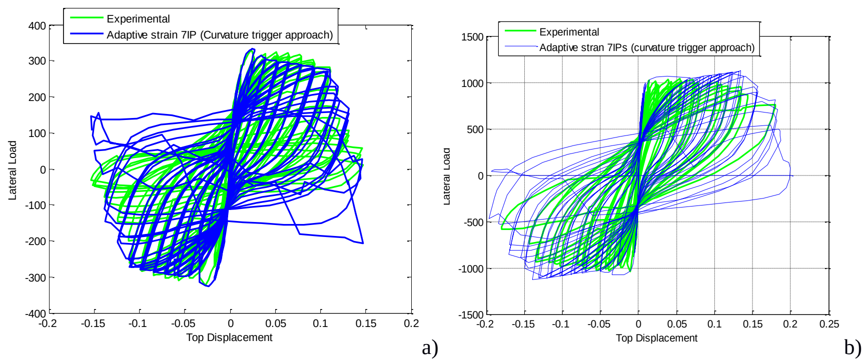

Figure 2. Comparison of the obtained results with the experimental local and global column responses

5 CONCLUSIONS

An application of a damage-following adaptive force based element has been presented and its performance against one experimental case with moderate axial loads was also presented. Simplified methods have been formulated, allowing for the use of adaptive beam formulations in OpenSees. Promising results were obtained, but further studies are necessary to assess the robustness of the implemented approach. Its use as a tool to evaluate the probabilistic comparison and reliability of more simple methods can be accepted, evaluating the impact of the modelling strategies selected by the analyst.

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